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The 4th ATW workshop took place from April 7-12, 2013 in the city of Aussois located in the French Alps. The conference was attended by 67 scientists who unanimously expressed their high satisfaction regarding the scientific quality of the meeting, the breadth and depth of the covered topics, and the quality of the organization. One of our goals was to encourage attendance by doctoral students and post-docs, and we were pleased to see this goal was reached again this time with the active participation of 20 students and post-docs who all presented posters. Geographic attendance was also highly diversified (27 participants from France, 16 from the US, 6 from Russia, 4 from Germany, 4 from the Netherlands, 3 from Australia, 2 from Switzerland, 2 from Italy and 1 from Saudi Arabia), with a strong representation from all the leading research groups internationally. Our goal of providing a wide forum for the dissemination of scientific information in the fields of the workshop was clearly met in this workshop. From a scientific point of view, the workshop featured 21 invited keynote lectures from top international scientists in the fields of plasma-assisted combustion and plasma-assisted flow control.

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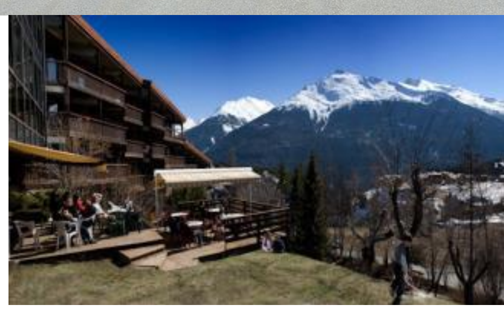
# 4th Aerospace Thematic Workshop: Fundamentals of Aerodynamic Flow and Combustion Control by Plasmas

Aussois, France
April 7-12, 2013

http://eucass.eu/atw2013

Organizers:

Christophe Laux
Svetlana Starikovskaya
Jean-Pierre Taran



The 4th ATW workshop took place from April 7-12, 2013 in the city of Aussois located in the French Alps. It receive much appreciated support from the following organizations, without which this workshop would not have been possible.

- European Office of Aerospace Research and Development
- Air Force Office of Scientific Research
- United States Air Force Research Laboratory
- Agence Nationale de la Recherche
- European Congress on Computational Methods in Applied Sciences and Engineering (EUCASS)
- European Collaborative dissemination of AEROnautical research and applications
- Centre National de la Recherche Scientifique (CNRS)
- Office National d'Etudes et de Recherches Aérospatiales (ONERA)

The conference was attended by 67 scientists who unanimously expressed their high satisfaction regarding the scientific quality of the meeting, the breadth and depth of the covered topics, and the quality of the organization. One of our goals was to encourage attendance by doctoral students and post-docs, and we were pleased to see this goal was reached again this time with the active participation of 20 students and post-docs who all presented posters. Geographic attendance was also highly diversified (27 participants from France, 16 from the US, 6 from Russia, 4 from Germany, 4 from the Netherlands, 3 from Australia, 2 from Switzerland, 2 from Italy and 1 from Saudi Arabia), with a strong representation from all the leading research groups internationally. Our goal of providing a wide forum for the dissemination of scientific information in the fields of the workshop was clearly met in this workshop.

From a scientific point of view, the workshop featured 21 invited keynote lectures from top international scientists in the fields of plasma-assisted combustion and plasma-assisted flow control. The conference was organized along the following themes:

- Monday April 8 :Aerodynamic flow control
- Tuesday April 9:l Plasma-Assisted Combustion / Diagnostics
- Wednesday April 10: Kinetics Modeling / Diagnostics
- Thursday April 11: Diagnostics / Kinetics
- Friday April 12 (morning) : Joint ECCOMAS-EUCASS Session on Advanced simulations

In addition, three poster sessions were organized on three evenings of the workshop. The topics covered included:

- Plasma-assisted aerodynamics
- Plasma-assisted combustion
- Discharges physics and kinetics

A visit was also organized in the afternoon of April 10 to the supersonic and hypersonic wind tunnels of ONERA in Modane, which is the premier site in France for such research. This visit was extremely well received by the participants (all of them elected to go on the tour).

## Contents

# 1. Flow Control and Steering Using On-Surface and Off-Surface Plasmas

*Richard Miles*
*Princeton University*

The use of plasma concepts for flow control has been an elusive goal, however new approaches are now showing promise. These include off-surface methods that can reduce drag, introduce steering moments and impact inlet performance of hypersonic vehicles as well as on-surface methods that allow separation control on air foils, ignition and flame speed control, and control of shock induced separation in inlets. Experiments demonstrating drag reduction and steering from plasmas were conducted in wind tunnel tests a decade ago (fig 1), however the viability of off surface methods for flight applications has been recently enhanced by experiments demonstrating that short pulse lasers can be used to guide the deposition of high power microwave and high power laser energy to specific locations in front of high speed vehicles. (Fig 2) New adjoint computational methods are being developed to determine the optimum the location for that energy deposition in order to minimize drag, produce lift or generate steering moments. These show that the marginal energy efficiency for drag reduction increases approximately quadratically with Mach number and is highly dependent on the shape of the vehicle.

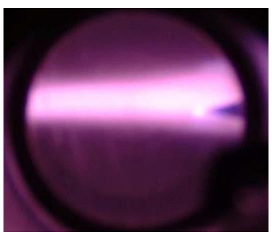


Figure 1: Wall Stabilized microwave driven plasma in front of a conical model in a Mach 3 flow

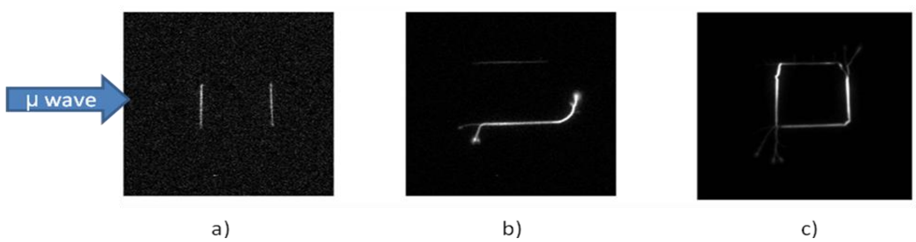



Figure 2: Laser designated line pairs along the microwave polarization (a) and orthogonal to the microwave polarization (b). When all four lines are simultaneously written, a square is formed with relatively

On-surface methods are also showing great promise. New approaches based on nanosecond high voltage, high repetition rate pulses are proving capable of reattaching separated high-speed flows through the creation of small shock wave driven streamwise vorticity. In addition the use of semiconducting overlay surfaces (Fig 3) may provide even more capability by eliminating reverse breakdown driven reverse velocity components that limit the effectiveness of dielectric barrier discharge (DBD) devices and by simultaneously eliminating reduced performance due to surface charge build up.

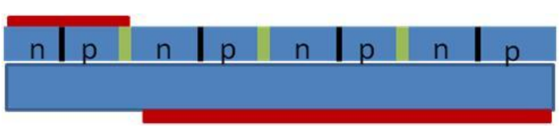



Figure 3: Diagram of an offset surface dielectric barrier discharge device with a semiconducting surface for suppression of backward breakdown and charge buildup

Support is gratefully acknowledged from AFOSR, NASA, DARPA, Boeing, Lockheed and Tech X

## 2. Advances in DBD plasma actuators

*Subrata Roy (Department of Mechanical and Aerospace Engineering, University of Florida, Gainsville).*

Dielectric barrier discharge caused by asymmetric arrangement of electrodes powered with a voltage difference is known to influence neighboring fluid flow. These actuators have significant impact on low speed flows. However, at higher speed ratios these actuators have limited influence due to poor coupling of plasma induced momentum to the surrounding flow. Several remedies to this limitation are being studied by the Applied Physics Research Group at the University of Florida.

These studies include:

1) Achieving order of magnitude higher thrust density using sheath dominated actuation with microscale actuators.

2) Fundamentally understanding the influence of gas and dielectric temperature on thrust saturation that inhibits performance of plasma actuators.

3) Using flow entrainment principles for naturally improving plasma induced gas velocity and attaining better penetration of momentum inducement into the bulk flow.

4) Fully three-dimensional coupling of plasma and its surrounding fluid flow using serpentine shaped actuators the curvature of which effects the vectoring of the induced jet.

5) Atmospheric to moderately low pressure testing of plasma actuators identifying several optimal control parameters for high-altitude operations.

Results from these studies give deeper insight into the operational mechanisms and possible options to improve performance of plasma actuators for applications in future energy efficient flow systems.

## 3. Recent advances in sparkjet actuators

*B. Cybyk, S. Popkin, B. Land, D. Van Wie*
*The Johns Hopkins University Applied Physics Laboratory*
*F. Alvi, T. Emerick*
*Florida A&M and Florida State Universities*

The SparkJet is a promising flow control actuator that is being investigated for enhancing the aerodynamic performance of flight vehicles. In its simplest form, the SparkJet actuator consists of a small volume containing electrodes and a single orifice. At modest operating frequencies, the SparkJet operation consists of three distinct repeating stages. In the first stage, a spark discharge is initiated between the electrodes to deposit energy into the gas within the SparkJet. This rapid energy deposition results in an increase in gas temperature and pressure. The second stage operation is a blowdown phase wherein the high-pressure gas exits the SparkJet through the orifice. This mass ejection initially occurs with choked flow at the orifice exit, but the flow becomes unchoked as the internal pressure decreases. The final stage of operation is referred to as the refresh phase, wherein the internal volume cools and refills with ambient gas. When sized appropriately, the SparkJet is capable of producing a synthetic jet with exhaust velocities sufficient to penetrate supersonic boundary layers and to serve as a flow control actuator for high-speed flows. Note that the basic SparkJet is solid state Zero Net Mass Flow (ZNMF) device with no expended materials.

A one-dimensional model of the SparkJet has been developed with the first stage modeled assuming instantaneous energy deposition and mass discharge stage modeled assuming isentropic flow. The model shows that the main characteristics of the device are driven by the ratio of deposited energy, $Q$, to gas energy, $E$, at the beginning of a cycle. Operation of the SparkJet with $Q/E > 2$ is projected to produce exhaust velocities greater 500 m/s.

Parametric calculations using two-dimensional and three-dimensional unsteady Reynolds-Averaged Navier-Stokes (URANS) techniques have also been used to demonstrate the basic operating principals of the SparkJet. Detailed calculations for actual device geometries and modeled energy deposition zones have demonstrated high frequency behavior associated with early wave propagation within the SparkJet, and the role of viscous effects on the mass discharge through small diameter exhaust orifices. Three-dimensional URANS calculations of the SparkJet operation have shown the ability of the produced exhaust jet to penetrate through a Mach 3 boundary layer.

Recent experimental bench-top testing of the SparkJet has verified many of the device operating principals. Direct measurements of the time variation of the internal SparkJet pressure were obtained in tests conducted using both a three-electrode triggered configuration and a two-electrode configuration in which a voltage pulse is used to initiate the discharge. With the specific electronic circuit used in the testing, the two-electrode configuration could be operated more reliability and with larger electrode gaps. Using a measure of efficiency defined as the peak cycle pressure divided by that predicted by the one-dimensional energy deposition model, the SparkJet efficiency was increased from 20% to 50% by using large electrode gaps when operated at $Q/E$ = 30. This increased efficiency is due to a higher effective heating of the internal gas. The device efficiency increased with lower $Q/E$ with a maximum measured efficiency of 80% at $Q/E$ = 5 with an electrode gap of 4 mm. The jet exhaust velocity and velocity of the resulting blast wave have also been measured during bench top tests using a micro-Schlieren imaging systems with a 10 ns light source timed to the SparkJet operation. Results show that the SparkJet produces peak jet velocities of 300–400 m/s with the exhaust velocity decaying during the mass discharge stage.

The ability of the SparkJet to modify supersonic flows has been demonstrated in testing in which a four-orifice version of a SparkJet was installed in the wall of a Mach 1.5 wind tunnel. This four-orifice device consisted of an internal volume increased by a factor of four compared to the baseline SparkJet design and operated using two electrodes in the common spark chamber used to feed each orifice. When operated in a single-shot mode, the mass discharge into the supersonic crossflow results in an oblique shock wave that varies in time following the discharge. Results show that the shock angle increases by approximately 5°, which is similar to the effect generated using a steady microjet operating at a pressure ratio of 3.2.

The simple operation of the basic SparkJet can be modified in potentially important directions. For example, the SparkJet can be operated at high frequencies wherein the three distinct stages described above merge and the impulse produced is lessened. In this mode, the SparkJet can serve as a source of high-frequency acoustic disturbances. The SparkJet can also be operated in conjunction with gas supply to the SparkJet volume. Operation in this manner can consist of a steady state operation that can be used in conjunction with pulsed operation. Finally, the SparkJet can be operated in individually addressable arrays wherein the spatial and temporal phasing of the array can be used to provide for more complex flow control. In the near future, the operating characteristics of the SparkJet in these new modes will continue to be explored together with investigations of flow control strategies associated with cavity flows and shock-wave/boundary-layer interactions (SWBLI).

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# 4. Laser Spike and SparkJet

*Doyle Knight*
*Department of Mechanical and Aerospace Engineering, Rutgers, The State University of New Jersey*
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### Laser Spike

Recent experimental developments in femtosecond laser technology have enabled the integration of laser and microwave discharge for creation of repeatable patterns of plasmoids in air. Earlier research in microwave discharge by Kolesnichenko et al at the Joint Institute for High Temperatures in Moscow demonstrated the capability for significant drag reduction through the interaction of a microwave-generated plasma with the shock system of an aerodynamic body at supersonic speeds. The filamentary microwave discharge pattern is particularly effective; however, the filament pattern is random and not strictly repeatable. A precursor femtosecond laser discharge combined with a microwave discharge provides the capability for repeatable filaments.

Our research examined the efficiency and effectiveness of a pulsed filamentary discharge upstream of a blunt cylinder at Mach 3. Time-accurate perfect gas simulations revealed several interesting features. First, the interaction of the filament with the blunt body shock results in a momentary drag reduction. However, in contrast to previous simulations, the drag reduction is associated with the momentary presence of the toroidal vortex (generated by the Richtmyer-Meshkov instability) at the corner of the cylinder face, thereby generating a low pressure and minimum drag. Second, while the effectiveness (i.e., relative reduction in drag) increases with filament temperature, the efficiency (i.e., energy saved to energy expended to create the filament) decreases.

### SparkJet

The SparkJet is a device for generation of a significant impulse using an electric discharge within a cavity with a converging nozzle. The SparkJet was developed at the Johns Hopkins University Applied Physics Laboratory by Cybyk et al, and subsequent research performed at the University of Texas at Austin and ONERA. The principal advantages of the SparkJet are rapid actuation time (i.e., milliseconds) and absence of moving parts.

Our initial research focused on the development of an analytical model for the single discharge of a SparkJet into a quiescent environment. The analytical model provides a closed form solution for the impulse generated by the SparkJet. Companion perfect gas simulations show excellent agreement with the analytical theory.

Our subsequent research examined the discharge of the SparkJet into a Mach 3 crossflow turbulent boundary layer. The simulations demonstrated a higher impulse than predicted by the analytical model for discharge into quiescent air.

## 5. Unsteady flow and acoustic noise control by DBD plasma actuators

*Ivan Moralev,Joint Institute for High Temperatures, Moscow, Russia*

In the lecture, two main problems were discussed:

1) Control of the acoustic noise of the turbulent high-speed jet by HF DBD plasma actuators:
2) Separation control DBD discharge on a bluff body and its applications to tonal noise reduction for cylinders and landing gear.

First part was based on the work published in [], with the collaboration with acoustic subdivision of TSAGI. Control of the broadband noise of the turbulent jet (Re~$10^6$, V=100—280 m/s) was performed by the HF DBD actuator, installed on the inner surface of the nozzle. Two main strategies were used.

Effect of steady actuation by stream-wise electrodes was studied, with the attempt to create stream-wise vortices in the shear layer of the jet. Such structures are created by shevrons and thought to be a reason of modes coupling in a shear layer. Preliminary studies have shown typical wall-normal velocities of 2-4 m/s in the actuator-induced disturbances in still air, this value significantly reducing at oncoming flow velocity increase and being hardly noticeable at 20m/s. No effect on the jet acoustic for the velocities >100m/s was obtained.

Effect of the unsteady actuation was studied with different electrodes configuration, for the discharge modulation frequencies 0.1—20 kHz. Main data were obtained by ring- type electrodes. It was obtained, that up to velocities of 200m/s broadband noise near the maximum can be significantly increased (+10dB) at low-frequency actuation (Sh~0.5)and decreased (-1.5 dB)at high-frequency actuation (Sh=3-10). Changes in the acoustic spectra correspond to changes in the shear layer structure and structures spatial wavelength. Mechanism of the actuation was analyzed. It seems that forcing of the BL by DBD leads to excitation of the Kelvin –Helmholtz instability in the shear layer. At relatively low velocities, effect can be referred to the volumetric force, created by the discharge. However, acoustic emission by the discharge channel can work as an acoustic source, and this is shown to be the main mechanism of actuation at increased velocities and discharge power input.

The second part of the talk was devoted to the tonal noise control on the bluff bodies by DBD discharge. Brief review was given of the background studied on the acoustic noise control by DBDs for cylinders and landing gear models. Since noise reduction for bluff bodies in strongly coupled with the task of vortex shedding, problem of unsteady separation control by DBD was further discussed.

Several results on the unsteady separation control on the transverse circular cylinder by unsteady HF DBD were shown. Discharge was organized on the span-wise electrodes prior to the average position of the separation point. Drag rise and wake diameter increase was obtained for low frequency excitation, drag decrease and wake diameter reduction was obtained for high-frequency excitation. Both cased caused mixing intensification in the wake shear layer, leading to decrease of average recirculation region size. Phase-locked visualization showed vortex shedding, triggered by the discharge pulses at the actuation frequencies.

HF DBD was found to be efficient for separation control on a cylinder up to oncoming flow velocities V~100m/s and Re~300 000. Also, three different electrodes configuration were studies: span wise – with discharge propagating co- and counter - flow, and stream-wise one. No qualitative difference was obtained between these three cases. Separation point dynamics, determined at Sh=0.3 from PIV data, was the same for all configurations. This means that mechanism of discharge actuation appears to be isotropic—therefore, turbulent spot production in the BL seems to be the likely explanation of the separation point dynamics and changes in the average flowfield.

## 6. Plasma-Assisted Combustion: From Benchtop Experiments to High-Speed Propulsion Applications

*Timothy Ombrello*

There is significant motivation for using plasma to aid combustion processes because of the desire for higher performance and more efficient propulsion systems in increasingly restrictive reactive environments. This necessitates the development of techniques for enhancing the rate of chemical heat release and is where energy addition via plasma can be beneficial. Unfortunately, the many energy coupling pathways create the significant challenge of attempting to understand the mechanisms of enhancement. This leads to different interrogation techniques to identify the mechanisms by either directly applying plasma to a reactive system or decoupling the interaction to isolate key species and pathways. Both of these techniques were discussed in the presentation ranging from examining the isolated effects of $O_2(a^1\Delta_g)$ and $O_3$ using well-defined benchtop plasma-combustion platforms, as well as kilohertz imaging of the ignition process in a turbulent flowing system using a nanosecond pulsed high-frequency discharge.

With regard to $O_2(a^1\Delta_g)$, significant effort was been placed on defining a platform to isolate the enhancement of flame speed, which spanned two systems. While a lifted/tribrachial flame system allowed for only a qualitative understanding of the relative effects of $O_2(a^1\Delta_g)$ with respect to $O_3$ in a $C_2H_4$ fueled system, the top level kinetic validation indicated that $O_2(a^1\Delta_g)$ reactions with parent hydrocarbon fuels and its fragments may not be important for predicting flame speed enhancement. Nevertheless, a more well-defined platform was developed using a Hencken burner at sub-atmospheric pressure where a range of equivalence ratios could be investigated. Significant characterization of the burner showed that the flame was nearly one-dimensional, minimally curved, weakly stretched, nearly adiabatic, and could be compared to numerical simulations with minimal corrections and extrapolations. When investigating the effects of $O_2(a^1\Delta_g)$ on $C_2H_4$ flame speed with the burner, the results followed the trends observed in numerical investigations by other groups showing that off-stoichiometric flames were enhanced more than stoichiometric flames by $O_2(a^1\Delta_g)$. More detailed follow-up studies are currently being performed to better quantify the enhancement.

In an attempt to investigate other plasma-produced species, $O_3$ was chosen because of its significant potential to enhance flame propagation. Again, $C_2H_4$ was used as a fuel in the Hencken burner platform at sub-atmospheric pressure, but now with the added diagnostic of particle image velocimetry to quantify the flame speeds. Interesting results were found where the enhancement of flame speed increased as a function of flame stretch rate for a fixed concentration of $O_3$. The increase was dramatic with a doubling of flame speed enhancement with a doubling of the stretch rate. Since stretch leads to decreased flame thickness, there was potential that increased pressure would also yield the same results. Numerical simulations showed a similar trend where increased pressure significantly enhanced flame speed for a fixed concentration of $O_3$. Therefore, $O_3$ appears to have the unique capability of greater levels of flame speed enhancement with increased stretch and increased pressure, which has significant potential for more realistic and practical combustion environments which can be at elevated pressures and have significant levels of turbulence.

Lastly, a nanosecond pulsed high-frequency discharge was applied for ignition in flow with significant levels of turbulence. Since some of the previous ignition enhancement using a nanosecond pulsed high-frequency discharge were performed in a quiescent chamber, there was interest in seeing if the benefits of such a system were applicable in a more realistic and practical propulsion environment. A simple point-to-point discharge system was used in a variety of gaseous and liquid hydrocarbon fueled flow through a duct with significant levels of turbulence. High-speed Schlieren imaging results showed that the nanosecond pulsed high-frequency discharge was significantly advantageous in terms of the initial ignition kernel growth when compared to a normal thermal arc discharge with comparable energy deposition. When the system was then applied to a pulse detonation engine, it was found that not only did the nanosecond pulsed high-frequency discharge lead to decreased ignition delay times, higher pulsation frequencies for a fixed energy deposition yielded even shorter ignition delay times. This indicated that the non-equilibrium nanosecond pulsed high-frequency discharge was coupling energy into the reactive system differently with a pooling of active species to provide a kinetic effect, which was similar to what was observed in previous work in a quiescent chamber.

In summary, fundamental studies in well-defined benchtop experiments can and have provided the foundations needed to move forward and apply the knowledge garnered to more realistic and practical combustion environments where there may even be elevated levels of enhancement because of the higher-pressure and turbulent environment conditions.

# 7. Electric Field Effect on Flame Stabilization

*Suk Ho Chung (King Abdullah University of Science and Technology)*

Electric field or plasma assisted combustion has been studied to improve such combustion characteristics as flame speed, flame stabilization, and pollutant emission. In case of electric field assisted combustion, lower power consumption and less flow disturbance could be expected as compared to plasma-assisted combustion.

In the reaction zone of a flame, positive ions have abundance in the order of $10^9$–$10^{12}$ /$cm^3$ produced from chemi-ionization. In an electric field, charged particles can be accelerated by the Lorentz force. This could lead to three effects on flames: (1) the diffusion flux of charged particles can be enhanced, (2) momentum transfer from accelerated charged particles to neutral molecules can generate bulk flow leading to the ionic wind effect, and (3) the enhanced kinetic energy of charged particles could also influence associated reaction rates.

Among these, the ionic wind effect has been most extensively investigated especially with DC electric field, while the effects of diffusion flux and chemical reaction on various flame behaviors have yet to be quantified.

To improve the stabilization characteristics of jet flames, the effects of AC and DC electric fields on the stabilization of jet flames have been investigated, including the influences on liftoff, blowoff, and reattachment for nonpremixed jet flames and on the liftoff of premixed bunsen flames. These findings will be discussed and the effect of bi-ionic wind will be emphasized.

Biography
Dr. Suk Ho Chung is Director of the Clean Combustion Research Center and Named Professor of Mechanical Engineering at KAUST since August 2009. He most recently served as a professor in the School of Mechanical and Aerospace Engineering at Seoul National University in Korea. Additionally, he served as Chair of the Department of Mechanical Engineering and Director of the Advanced Automotive Research Center. He has published over 100 articles in refereed international journals. He is a Fellow of the American Society of Mechanical Engineers (ASME). He served as a Board of Director and International Secretary of the Combustion Institute. His services include Vice President of the Korea Society of Automotive Engineers and the Korea Society of Combustion, as an editorial board member of Combustion and Flame and as the editor-in-chief of International Journal of Automotive Technology. He earned his doctoral and master's degrees in Mechanical Engineering from Northwestern University, Illinois, in the United States. He holds a bachelor's degree in Mechanical Engineering from Seoul National University in Korea.

## **8.** Plasma assisted combustion in a Rapid Compression Machine

*Guillaume Vanhove (Lille).*

A novel experimental scheme to study ignition of combustible mixtures at high pressures under the action of a high-voltage nanosecond discharge has been developed. The experiments were performed in the combustion chamber of a rapid compression machine (RCM) with a specially designed system of electrodes. Nanosecond surface dielectric barrier discharge (SDBD) provided two-dimensional low-temperature non-equilibrium plasma in the vicinity of the end plate of the combustion chamber. Radially symmetric plasma channels triggered multi-point ignition of gas mixtures at controlled pressure and temperature. Ignition delay times and energies deposited in the gaseous mixtures by the discharge were measured for different parameters of high voltage pulse for positive or negative high-voltage pulse. Preliminary numerical analysis of the ignition under the action of a pulsed nanosecond discharge has been made; it was shown that production of atomic oxygen by the discharge, will modify the ignition chemistry by perturbation of the radical pool. Experiments and calculations were performed in methane-oxygen and n-butane-oxygen mixtures with a stoichiometry between 0.3 and 1 diluted by 70-76 % of Ar or nitrogen for initial temperatures between 600 and 1000 K and pressures between 6 and 16 bar.

# 9. Control of combustion dynamics using plasma discharges

*Jonas Moeck (TU Berlin)*

Combustion instabilities are a well-known issue for the design of modern combustion chambers in aeroengines and stationary gas turbines for power generation. Unsteady heat release rate from the flame interacts with the acoustic modes of the combustion chamber and results in high-amplitude pressure pulsations. The negative effects associated with combustion instabilities – structural fatigue, increased heat transfer to the combustor walls, possibly increased emissions – are in most cases unacceptable. Therefore, the occurrence of this dynamic phenomenon effectively results in a limited operating range with lower power output and decreased efficiency. It is therefore of prime importance to find effective means for mitigating these instabilities. Passive devices such as acoustic dampers are traditionally used in full-scale engines but typically are effective in a very narrow operating range only. Active control approaches are flexible but need robust and efficient actuators, which presently are not readily available.

Over the recent years, the application of non-equilibrium discharges for plasma-assisted combustion has shown significant potential for affecting key combustion properties, for example, the ignition delay or the lean blow-off limit. These achievements suggest that this approach could be used for control of combustion instabilities as well. In this talk, we present some results related to our work on applying nanosecond discharges to suppress acoustically induced combustion dynamics. Open and closed-loop strategies are considered. In a turbulent bluff-body stabilized flame configuration, the transient response of the flame to nanosecond discharges is found to be of the order of a few milliseconds, which would generally allow to dynamically interfere with self-excited oscillations related to the lowest acoustic modes of practical configurations, which are typically found at frequencies around a few hundred Hz. This time scale is found to dominantly result from convective transport of heat and reactive species from the recirculation zone in the wake of the bluff body, where the discharges are applied, to the flame base.

It is shown that open-loop application of nanosecond discharges can achieve a significant attenuation of thermoacoustic oscillations. This may be attributed to the effect the discharges have on the acoustic response of the flame. Measurements of the flame transfer function, the frequency-domain ratio of the normalized perturbations of the integral heat release rate to normalized fluctuations in the approach flow, with and without plasma discharges illustrate this effect. It is found that in certain frequency ranges, the gain of the flame response is significantly decreased with plasma discharges, effectively reducing the sensitivity of the flame to acoustic perturbations and thus making it less prone to combustion instability.

Closed-loop control of combustion dynamics is applied in an atmospheric combustor test-rig with a swirl-stabilized flame. The unsteady combustor pressure is used as a feedback signal. An extended Kalman filter in combination with a phase-shifter generates a gate signal that modulates the high-frequency pulse train driving the nanosecond discharges. The gate signal shares the fundamental frequency of the natural combustor pressure oscillation and is shifted in phase such that an attenuation is achieved. A variation of the phase shift shows that the oscillation amplitude strongly depends on this control parameter. This demonstrates that the plasma discharges interfere dynamically with the self-excited oscillations in the combustion chamber.

The proposed actuator technology based on nanosecond discharges is attractive for combustion instability control because it does not involve any moving parts and is thus very robust without suffering from any inherent limitation in terms of bandwidth. More fundamental investigations on unsteady plasma–flame interaction in the future will be necessary to uncover the full potential of this approach for controlling combustion instabilities.

## 10. Supersonic Flow Control by Microwave Discharge and Non-equilibrium Processes in Viscous Gas Flows

*Elena Kustova (Saint Petersburg State University, Department of Mathematics and Mechanics, 28 Universitetsky pr, 198504 Saint Petersburg, Russia, elena_kustova@mail.ru)*

The talk deals with two different aspects of non-equilibrium gas flows: 1) experimental study for a possibility of flow control using microwave discharge, and 2) advanced theoretical study of the viscous flow effects on the rates of chemical reactions and vibrational relaxation.

In the first part, the experimental results obtained at the supersonic facility TBS in Saint-Petersburg State University (SPSU) are discussed. A brief overview of the facility is presented. It provides a flow up to 60mm diameter, with fixed Mach numbers from 1.3 to 3. The static pressure is 25-100torr, the stagnation is temperature is about 300K. The facility is equipped with the microwave generator (frequency 9,6GHz, pulse power up to 250kW, pulse duration 2μs, repetition rate 1-30Hz) used to create plasma structures near the blunt body nose. The energy deposition in a supersonic flow leads to the vortex creation, the vortex destroys the bow shock wave, which leads to the pressure drop and drag reduction. The experimental technique was proposed by our colleagues from Joint High Temperature Institute (Moscow), and its realization was carried out in SPSU. Recently the facility was upgraded in order to use the laser spark to control the discharge location, geometry and intensity. We expect new experimental results in the very next future.

In the second part, some non-equilibrium effects arising in viscous flows and basically neglected in the computational fluid dynamics are discussed. It is shown that in a viscous flow, strong coupling between normal mean stress and rates of non-equilibrium processes (chemical reactions, vibrational transitions) takes place. The rates of chemical reactions and vibrational energy relaxation depend on the velocity divergence and on the affinities of all other reactions. It leads to the violation of the mass action law and Landau-Teller relation in a viscous flow. Some preliminary numerical estimations are given. Brief discussion of the role of electronic excitation in the heat transfer is also discussed.

## 11. Low temperature kinetic mechanisms in combustion: opportunities for combustion modification

*Charles K. Westbrook (Lawrence Livermore Laboratory)*

Ignition plays a non-trivial role in most combustion systems. In addition to starting the combustion in reciprocating engines, gas turbines, and many other practical systems, ignition in the form of engine knock can destroy a spark-ignition engine, and optimal ignition can assure high combustion efficiency and minimal toxic emissions from combustion systems. This presentation summarized the major chemical kinetic features of hydrocarbon fuel ignition and many of the ways that ignition can be accelerated or retarded to modify the performance of combustion systems to achieve a desired result. One theme of this presentation was to suggest methods where plasma processes might be used to assist or control hydrocarbon ignition.

Methods for modifying ignition can involve adding to the fuel small amounts of certain chemical species that act primarily by supplying extra amounts of chemical radical species at specific times selected to have the greatest influence. Sometimes these additives can encourage or advance ignition by providing radicals at times earlier in the ignition process than the original fuel/oxidizer mixture can provide. Examples of this effect are often called diesel ignition enhancers such as ethyl-hexyl nitrate, but they can also be relatively unstable species such as ozone or many types of peroxide species. Silane is another additive that can advance ignition very effectively. Additives can also retard ignition by removing radical species from the reactive gas mixtures. This is most often employed to inhibit or delay the onset of engine knock, and in the past, gasoline additives such as tetra-ethyl lead or methyl tertiary butyl ether have been used as antiknock additives.

The molecular structure of the fuel itself contributes a great deal to its ignitability, and this lecture summarized the major structural factors involved. At relatively low combustion temperatures, hydrocarbon fuels react slowly, largely via abstraction of H atoms from the fuel molecule. This is followed by addition of molecular oxygen at the site where the H atom was removed, and a complex sequence of isomerization and addition reactions is the result. This sequence of low temperature reactions produces a modest (~25-50K) amount of heat release, heating the reactive fuel/oxidizer mixture so that it can fully ignite at times earlier than would have been possible without this modest amount of low temperature heat release. This low temperature reactivity continues for only a small range of reaction temperatures, usually from 650 - 800K, and this effect is often called a cool flame. The shutoff of low temperature reactivity that occurs about 800K is due to the advancing temperature making the addition reaction of molecular oxygen to the alkyl fuel radicals unstable, and this is often termed the "negative temperature coefficient" (NTC) of reactivity.

The molecular structure of different fuels can encourage or discourage low temperature reactivity, and the main factors include the types of C-H bonds (i.e., primary, secondary or tertiary) have a significant impact, as does the total size of the fuel molecule and the presence or absence of C=C double bonds within the fuel molecule. Some fuels, such as benzene, toluene, and methane show an almost complete lack of low temperature kinetic reactivity, while n-alkane hydrocarbon fuels with long chains of secondary C-H bonds have the largest NTC and low temperature reactivity. All of these structural factors are reflected in the octane or cetane numbers of automotive fuels.

## 12. Kinetics of plasma-assisted ignition: mechanisms and problems of computer simulations

*Nickolay L. Aleksandrov (MIPT)*

The mechanisms of plasma-assisted ignition and plasma-assisted combustion are discussed. Electron energy branching and production of active species in non-equilibrium discharge plasmas are considered as a function of reduced electric field for air and fuel-air mixtures. The effect of rotationally, vibrationally and electronically excited molecules on chain-radical ignition of combustible mixtures is studied. Particular attention is given to the influence of atom and radical production in discharge plasmas on ignition acceleration. Ionic mechanisms of oxidation with low energy threshold are mentioned. Ignition and oxidation of hydrogen- and hydrocarbon-containing mixtures after high-voltage nanosecond discharges are considered below and above self-ignition threshold. It is shown that the combined production of vibrationally excited nitrogen molecules and oxygen atoms can lead to the synergistic effect on fuel oxidation in fuel-air mixtures after a streamer discharge bridging the discharge gap. The channels for fast (on a nanosecond scale under standard conditions) gas heating in non-equilibrium discharge plasmas and their influence on ignition are discussed.

The kinetic problems of numerical simulation of plasma-assisted ignition are examined. Simplified kinetic models to simulate production of active species and fast gas heating in discharge plasmas are investigated. Uncertainty in the rates for processes with excited species and its influence on the simulation results for plasma-assisted ignition are demonstrated.

# 13. Kinetics of Plasma Assisted Hydrocarbon Oxidation in Flow Reactors

*Richard A. Yetter, Nicholas Tsolas, Kuni Togai (The Pennsylvania State University, University Park, PA USA*
*Igor Adamovich (The Ohio State University, Columbus, OH USA)*

Pyrolysis and oxidation kinetics of $C_1$-$C_4$ hydrocarbons were studied with and without high voltage nanosecond plasma discharges at atmospheric pressure from 400 to 1250 K. Experiments were performed in a nearly isothermal flow reactor using reactant mixtures diluted with argon and nitrogen to minimize temperature changes from chemical reaction. At the end of the isothermal reaction zone, the gas temperature was rapidly lowered to quench reactions. Gas composition was then determined using inline Fourier transform infrared analysis and by sample extraction and storage in a multi-position valve for subsequent analysis with gas chromatography. Experiments were performed by fixing the flow rate or residence time in the reactor, and varying the temperature to achieve a reactivity map. The discharge region occupied approximately 15% of the total length of the isothermal reaction zone and could be placed anywhere along the length of the reactor, e.g., at the beginning of the isothermal zone to study coupled interactions between the chemistry initiated in the plasma and that which continued downstream in the high temperature afterglow region or at the end of the isothermal region where the chemistry was rapidly quenched once the flow left the discharge region. Discharge voltage and frequency were varied to study their effects on the reaction. The fuels studied were hydrogen, carbon monoxide, methane, ethylene, propane, and butane.

The discharge was found to enhance all reactions from 400 K to the self-ignition temperature of the fuel. For ethylene, kinetic results with the discharge indicated that pyrolysis type reactions were nearly as important as oxidative reactions in consuming ethylene below 750 K. Above 750 K, the thermal reactions coupled to the plasma reactions providing further oxidation. Modeling analysis of plasma assisted pyrolysis revealed that ethylene dissociation by electron impact resulted in the direct formation of acetylene and larger hydrocarbons by way of the vinyl radical. During plasma assisted oxidation, direct dissociation and excitation of oxygen led to further fuel consumption, and enhanced low-temperature oxidative chemistry by effective production of methyl and formyl radicals. At the highest temperatures, the radical production by neutral thermal reactions became competitive and the effectiveness of the plasma discharge decreased.

Hydrogen oxidation showed no thermal reaction until 865 K, where the second explosion limit occurs at atmospheric pressure, at which point the hydrogen was rapidly consumed within the residence time of the reactor with any further increase in temperature. With the nanosecond plasma discharge, reaction occurred at all temperatures and exhibited an autocatalytic acceleration from 400 K up to approximately 800 K where all the hydrogen was consumed. Both propane and butane exhibit cool flame chemistry at pressures above atmospheric over the narrow temperature range of ~650-750 K; however, at atmospheric pressure, only the intermediate/high temperature thermal reaction is observed above ~950 K. The addition of the plasma resulted in significant reaction over the entire temperature range for both propane and butane with low temperature chemistry occurring between 400 and 700 K characteristic of alkylperoxy radical formation, isomerization to the hydroperoxyalkyl radical, and dissociation to form aldehydes and ketones and intermediate temperature chemistry between 700 and 950 K characterized by β-scission of the initial alkyl radical to form alkenes and smaller alkanes.

# 14. Laser Diagnostics for Turbulent Combustion

*Armelle Cessou (CORIA UMR 6614, Normandie Université, CNRS Université et INSA de Rouen, 76801 St Etienne du Rouvray, France*

Laser diagnostics have shown their interest for investigating reacting flows for many years. Investigation of turbulent combustion presents some specificity due to the multi-physics and multi-scale feature of flame and turbulence properties. Many interactions are involved between aerodynamics, mixture, chemistry and even plasma or electric field in plasma assisted combustion. The range of time scale of all these phenomenon spans from a few microseconds to milliseconds, or even seconds for aerodynamics, and are associated to length scales spanning from microns to centimeters, or even meters in large scale applications like furnaces.

Turbulent flame properties are controlled by velocity, mixture and temperature gradients and numerous interactions occur between mixture, turbulence, heat release and chemistry. All these properties lead to specific requirements for laser diagnostics in terms of time resolution, spatial resolution, diagnostic combination for joined and conditional analysis, 3D investigation or failing that, 2D, and time-resolved analysis. These specific requirements are illustrated by two examples of investigation of partially premixed combustion: an outwardly propagating flame through mixture stratification and the stabilization of lifted flame assisted by DC electric field. These two examples are chosen to illustrate the specificity of turbulent flame investigation: need of large field of view with spatial resolution for mixture field characterization and an example of a specific development for PIV (Balusamy et al., Experiment in Fluids, 2010), the laser sheet profile correction for single-shot quantitative measurements. The interest of joint analysis is illustrated by the evidence of a memory effect in stratified combustion (Pasquier et al., Proceeding of the Combustion Institute, 2007) and the change in the flow field upstream the base of a lifted flame when the stabilization is enhanced by an electric field (Cessou et al. Experiment in Fluids, 2012).

Spontaneous Raman Scattering (SRS) is also an essential mean of turbulent flame investigation since it is one of the only diagnostics measuring major species as well in fresh gases as in burnt gases. The measurements by SRS in turbulent flames impose specific requirements: single-shot measurements, spatial resolution, multi-species investigation which make SRS a powerful diagnostics for investigating nanosecond pulsed plasmas. The development of SRS for turbulent combustion makes SRS a useful method for obtaining valuable information leading to better understanding of the energy deposit of pulsed air discharges, especially through the quantitative description in time and also space of the thermal structure of the molecules and of their vibrational excitation (Lo et al., Applied Physics B, 2012). Thus SRS provides a precise description of vibrational excitation by measuring the density of each vibrational level and estimating local pressure on the basis of the total density measured. All this information provides an interesting validation database for modeling pulsed air discharges at high pressure, especially with additional future measurements to describe discharges, such as spontaneous emission.

## 15. Optical diagnostics for automotive engine research

*Guillaume Pilla (IFP-Energies Nouvelles)*

For car manufacturers and especially engine designers the main constraints come from pollutant emission regulations. Thus exhaust limitations are imposed for unburned hydrocarbons, carbon monoxide, nitric oxides and particles. Though there is no specific limitation for carbon dioxide, it is of great need to minimize its emission to ensure reduction of the greenhouse effect impact of ground transportation. To help engineers build the engine of tomorrow, the physics involved in the formation process of these species need a better understanding. Over the past 15 years new combustion strategies have emerged (downsizing, downspeeding, dilution, ...), implying new technologies (direct injection, turbocharging, exhaust gas recirculation, ...) and introducing new physics (liquid films, flame propagation, wall / flame interaction, ...). In this context optical diagnostics for engines are great tools to provide qualitative and quantitative information on a large variety of phenomena occurring in the combustion chamber.

As an example, the usefulness of optical diagnostics can be demonstrated in an attempt to understand the soot formation mechanism in a gasoline direct injection engine. In this type of engine, the main particles are produced during the warm-up phase. Two different paths for soot production are known, one involving wall impingements and liquid films, the other involving mixing heterogeneities. To thoroughly study soot formation, it is mandatory to track every steps of each path. Therefore a complete set of optical diagnostics has been chosen: high speed Mie scattering to follow liquid droplets and spray evaporation process, vapor LIF to provide 2D measurements of air-fuel ratio, LII and direct high speed imaging to follow soot particles in the chamber. For the purpose of this study a specific diagnostic has also been developed to measure liquid films on the cylinder and piston walls. Finally, to ensure the representativeness of the transparent engine compared to a full metal engine, wall temperature has been measured using a laser induced phosphorescence technique. With this setup and an adequate protocol, different mechanisms for soot formation have been identified and prioritized and leverages to minimize them have been identified, thus demonstrating the great role of optical diagnostics in automotive engine research.

# 16. Laser Electric Field Measurement and Ultra-Fast Imaging Spectroscopy in Atmospheric Pressure Plasmas

*Uwe Czarnetzki (Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44801 Bochum, Germany, uwe.czarnetzki@ep5.rub.de)*

Electric fields in plasmas represent a key parameter for understanding the underlying physics of discharges. Non-invasive laser diagnostic techniques for measuring electric fields in plasmas are reasonably developed in the low-pressure regime, typically below a few 100 Pa. At atmospheric pressure these techniques fail mostly due to strong quenching of excited states.

In 1995 a novel technique was developed at the Lebedev Institute being insensitive to quenching and designed particularly for application at atmospheric or higher pressures. The basic concept of this technique is similar to the well established CARS scheme but here one of the laser fields is effectively replaced by a static field. In consequence a coherent and well directed signal wave in the IR is generated with the intensity being proportional to the square of the static field strength. The frequency of this signal wave is given by the energy difference between the two vibrational states used in the CARS process. Raman active molecules in the feed gas of the discharge serve as the medium. Originally, the technique was applied to hydrogen but recently it could be extended to nitrogen.

In this presentation the basic concept of this technique is introduced and application is made to ns-discharges in hydrogen and nitrogen. The laser electric field measurements are supplemented by current and voltage measurements and in particular ultra fast emission spectroscopy using either an ICCD camera of a streak camera. Experimental requirements and calibration techniques are discussed. The field sensitivity of the laser spectroscopic technique depends on the molecular and the pressure. At atmospheric pressure the minimum measured electric fields are 2 V/mm in hydrogen and 30 V/mm in nitrogen. Minimum pressure for carrying measurements of fields of a several 100 V/mm is 250 Pa for hydrogen and 4000 Pa for nitrogen.

Detailed time and space resolved measurements are carried out in a ns-discharge between two parallel electrodes with a discharge gap of 1.2 mm. In this case the current and field measurements can be combined to infer also the plasma density. Alternatively, the density evolution can be calculated from the measured field using the Townsend ionization formula.

In this way time and space maps of the electric field, the plasma density, and the emission of selected atomic and molecular transitions can be constructed. In case of hydrogen, comparison is made to PIC/MC simulations and very good agreement is found. From these data a detailed understanding of the discharge development on a ns time-scale can be developed.

Finally, an outlook on perspectives for further improvement and extension of the technique is given and the perspective of using laser spectroscopic field measurements for discharge development is discussed.

# 17. "CARS, Raman, and LIF Measurements of Diffuse Single Filament Nsec Pulsed Discharges"

*Walter R. Lempert (The Ohio State University, Columbus, OH 43210)*

Recent measurements, and modeling predictions, are presented of the temporal evolution of $N_2$ vibrational distribution function, and OH and NO mole fractions in a diffuse single filament point-to-point non-equilibrium nsec pulsed discharge in pure $N_2$, air, and air/fuel mixtures. Specifically psec CARS and spontaneous Raman spectroscopy are used to measure time-resolved vibrational level populations of $N_2$. Results for $N_2$ at P=100 Torr are summarized in Fig. 1, which shows experimental and modeling predictions for temperature, first level $N_2$ vibrational temperature, and total vibrational quanta per molecule in levels v=0-8, for which measurable population was observed. It can be seen that the number of quanta increases after the discharge pulse, by a factor of ~2-3 for time delays of ~10–200 μs. This suggests that additional energy is loaded into $N_2$ vibrational mode after the pulse. This is at variance with modelling results, which predicts the number of quanta to remain nearly steady for up to ~200 μsec after the pulse, since V-V exchange conserves the number of quanta in the $N_2$ vibrational mode. It can also be seen that the model overpredicts the temperature and underpredicts vibrational temperature, indicating that a lower fraction of discharge input energy thermalizes on this time scale. These results, as well as measurements of time-resolved $N_2$(v=0-8) vibrational level populations, suggest that a significant fraction of energy stored in $N_2$ excited electronic states generated by electron impact is transferred to the vibrational mode of $N_2$(X) state, rather than to heat, e.g. by energy pooling processes. Similar results are obtained in air at P=100 Torr and from spontaneous Raman scattering measurements, in which $N_2$(v=0-12) were detected.

Figure 2 shows the temporal evolution of NO number density in air and ethylene/air at φ = 0.48 and total pressure of 40 Torr. In both cases it can be seen that NO number density rises rapidly, on time scale of ~10 μs, a result which modeling predictions ascribe to the rapid reaction of O atoms with electronically excited nitrogen, O + $N_2$(A) → NO + N. The decay , which is orders of magnitude slower in the ethylene mixture, is believed to be due to the reverse Zeldovich process, O + $N_2$ ← NO + N. In fuel mixtures at low temperature N is lost rapidly due to processes such as N + $HO_2$ → NO + OH. Measurements of N atoms and OH radical in this system are planned for the near future in order to confirm this hypothesis.

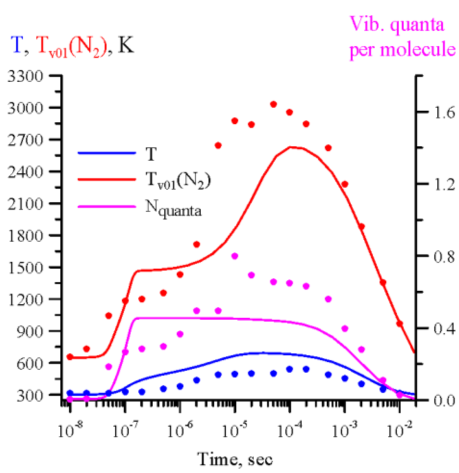


Figure 1. Predicted and experimental (psec CARS) temperature, first level $N_2$ vibrational temperature, and vibrational quanta per $N_2$ molecule in a pin-to-pin discharge in $N_2$ at P=100 torr.

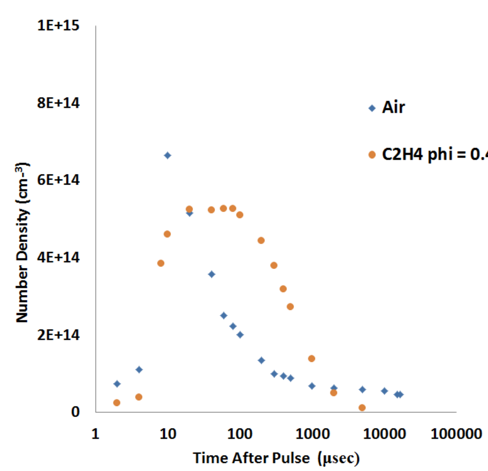


Figure 2. Temporal evolution of NO number density in air and φ = 0.48 ethylene/air point-to-point nsec discharge a P = 40 Torr.

## 18. Optical Diagnostics in Hypersonic Flows and Plasmas

*Sean O'Byrne (University of New South Wales, Canberra, Australia)*

This presentation will outline the work being done at UNSW Canberra on understanding hypersonic flows in thermal nonequilibrium and initial investigations of laser-induced plasmas and short-duration discharges. We present two-component velocity and rotational temperature measurements in a hypersonic nonequilibrium separated flow using planar laser-induced fluorescence, showing the spatial distribution of flow parameters. We will present this work in the context of improving the modelling for low-density hypersonic separated flows in thermal nonequilibrium, an important class of flows that have proved very difficult to accurately model. We will also discuss resonantly-enhanced shearing interferometry, a density-sensitive flow visualisation technique for low-density flows and plasmas that has a sensitivity much greater than standard Schlieren systems, making a powerful combination with high-speed cameras. We will also present measurements of velocity and temperature in plasmas using emission spectroscopy and tuneable diode laser absorption spectroscopy. Finally, we will present measurements of the effect of laser-spark induced plasmas on ignition in a supersonic combustor.

## 19. Advanced Simulation of combustion phenomena: from spark discharge to stable combustion

*Bénédicte Cuenot et al. (CERFACS/CFD Team, Toulouse, France)*

**The presentation gives some insight on the current status and future trends of combustion simulation, with a particular focus on the problem of ignition.**

Large Eddy Simulation (LES) has recently become the most developed and used tool for the study of turbulent combustion in aeronautical engines. In this approach, the large scales of the turbulent flow are directly resolved, while only the small scales are modeled via a diffusion-like term. The consequence is an excellent prediction of the turbulent flow, which explains the important and still increasing success of LES in both academia and industry.

The presentation first describes the basics of LES for turbulent combustion. Many complex physics interact with turbulence: combustion chemistry, spray, acoustics, etc. and sub-grid scale models are also needed for them. LES requires high order numerical schemes and high quality meshes, usually unstructured to correctly describe real geometries. After validation on the PRECCINSTA burner, application to a real helicopter engine is described. Finally full annular combustion chamber simulations are presented. Such simulations are required for the study of azimuthal thermo-acoustic instabilities and highlight the necessity of high performance computing.

The second part of the talk is devoted to the problem of ignition. This is a complex transient process, successively controlled by different physical phenomena: first the igniter system, through an electrical discharge, creates a small flame kernel that grows until transitioning to a turbulent flame; this turbulent flame in a second stage propagates upstream towards the injector nozzle to establish a stabilized flame in a first sector of the burner; finally the last phase consists of flame propagating from one sector to the other, until the full annular burner is ignited. Various LES of the complete process including the three phases are shown and demonstrate the correct prediction of the two flame propagation phases. On the contrary, as the first kernel phase is modeled with rough assumptions, simulations do not always reproduce it correctly. This is due on one hand to the high uncertainty on the energy deposited by the spark, and on the other hand to the highly variable conditions (in terms of equivalence ratio and velocity) that may be encountered at the time and location of discharge. This last point leads to the concept of ignition probability, which allows to characterize the cold flow in terms of ignitability.

Finally the third part of the presentation introduces the concept of multi-physics simulations. One strategy to level a number of uncertainties in LES, for example thermal boundary conditions, is to include their controlling mechanisms in a CFD-coupled approach. This may be realized with an optimum use of massively parallel machines, via dedicated code-coupling softwares such as O-Palm developed at CERFACS. Multi-physics and multi-scale simulations are the targets for the upcoming exascale parallel computations.

# 20. Modeling of plasma-assisted combustion

*Laxminarayan Raja (UT Austin).*

# 21. Parallel computing for advanced simulation

*François-Xavier Roux (ONERA).*

Numerical simulation in science and engineering tries to be more and more accurate. This means capturing smaller and smaller scales and more and more complex phenomena. The numerical models are larger and larger and the requirements, both in terms of memory size and of computing power, have no limits. Computers have.

The improvement in semi-conductor technology has allowed a factor of two increase of the frequency of the micro-processors up to the years 2004-2005. Since then, the increase of the number of transistors per chip has continued, as predicted by Gordon Moore in 1965. Higher frequency requires higher current intensity, and heat dissipation and power consumption have become such an issue that the frequency has stagnated since then. Nowadays, the continuing computing power increase is only based on parallelism: multiple arithmetic units in each core, multiple cores on a single chip, multiple processors.

The issue with parallelism is that it is not transparent to the user.

Furthermore, the main hardware issue for parallel architecture is the memory. How to provide data to all the arithmetic units at the same time is a real challenge. Furthermore, the larger a memory unit, the higher the latency for a random access. So the memory system must be parallel also. In practice, the memory has a hierarchical architecture, with small and fast memory units near the cores, the cache memories, and larger memories shared by a group of cores. But a memory cannot be shared by too many cores without causing a bottleneck. So scalable systems feature a distributed memory architecture, which means networked compute nodes, at the highest level.

This entails that the main issue with the efficient use of parallel machine lies in the design of methods and algorithms leading to spatial and temporal locality of data. This means that the global data structures must be split into blocks that can fit in the fast memory units close to the cores and that are used many times before being copied or sent to another memory level.

In computational linear algebra, block strategy is the methodology of choice to obtain parallel algorithms featuring a good spatial and temporal locality of data.
For numerical simulation in mechanics or physics based on the discretization of partial differential equations with meshing of the spatial domain, splitting the problem data structure means splitting the mesh. Domain decomposition methods are efficient parallel solution methods based on mesh splitting. The domain decomposition approach may be extended to the case of multi-physics simulation using code coupling. In both cases, the global simulation can be performed by coupling, via message passing, simple software modules dealing each with a single subdomain and a single numerical model. This methodology for designing simulation code is not only suitable for enforcing spatial and temporal locality of data, and henceforth suitable for parallel efficient computing, it can also be considered as a general methodology for building complex simulation tools by coupling simple modules without integrating them in a single complex software.

# Poster session 1. Aerodynamics

| N | Presenting author | Poster title: Aerodynamics | Affiliation of presenting author |
|---|---|---|---|
| 1 | Stefan Brieschenk | Laser-induced plasma ignition studies for scramjet propulsion | UNSW, Canberra |
| 2 | Nathan Calvert | Boundary layer velocity measurements with FLEET | Princeton University |
| 3 | Philippe Castera | Application of linear sliding discharges for flow control: study of the energy coupling mechanisms | ONERA, Ecole Centrale Paris |
| 4 | Victor Golub | Dielectric barrier and sliding discharges as a way of wingtip vortex destruction | Joint Institute for High Temperatures, Moscow |
| 5 | Carolyn Jacobs | Ablation/Radiation studies in the Ecole Centrale Plasma Torch Facility | EM2C Ecole Centrale Paris / U. Queensland |
| 6 | Konstantinos Kourtzanidis | Numerical modeling of microwave discharge actuators | ONERA–DTIM, Toulouse |
| 7 | Aleksandr Kuryachii | Creation of artificial disturbances in subsonic jet by force impact of DBD actuator | Central Aero-hydrodynamic Institute, Zhukovsky, Moscow region |
| 8 | Alexandre Likhanskii | Shock wave boundary layer interaction control using pulsed DBD plasma actuators | Tech-X Corporation |
| 9 | Olivier Leon | Noise control by plasma discharges (EU Orinoco project) | ONERA / TsAGI |
| 10 | Christopher M. Limbach | A systematic adjoint design approach to controlling hypersonic flows by guided energy deposition | Princeton University |
| 11 | Philip Peschke | Nanosecond pulse DBD actuators in sub- and transonic flow | EPFL |
| 12 | Dmitry Rusyanov | Cross-flow instability control in compressible boundary layer by means of DBD actuators | Central Aero-hydrodynamic Institute, Zhukovsky, Moscow region |
| 13 | Irina V. Schweigert | Control of electron density in plasma sheath near the surface in gas flow with DC discharge and magnetic field | Institute of Theoretical and Applied Mechanics, Novosibirsk |
| 14 | V.I. Shalaev | Analytical model for flow asymmetry control by plasma discharge | Moscow Institute of Physics and Technology |
| 15 | Umar A. Sheikh | Re-entry radiative heating studies in the vacuum ultraviolet | EM2C Ecole Centrale Paris / U. Queensland |
| 16 | Andrey Yu. Starikovskiy | Boundary layer - shock wave interaction control by plasma actuators in high speed flow | Princeton University |

# Poster session 2. Combustion

| N | Presenting author | Poster title | Affiliation of presenting author |
|---|---|---|---|
| 1 | Nikolay Aleksandrov | Ignition in acetylene-containing mixtures after nanosecond discharge | Moscow Institute of Physics and Technology |
| 2 | Mouhamed A. Boumehdi | Ignition of combustible mixtures by surface discharge in a rapid compression machine | University of Lille 1 |
| 3 | Sean O'Byrne | Baseline distortion in a log-ratio diode-laser-based temperature sensor | School of Engineering and IT, Canberra |
| 4 | Tat Loon Chng | Towards Absolute Measurements of Atomic Oxygen in Flames Using Radar REMPI | Princeton University |
| 5 | Nikolaj Kuntner | Non-thermal plasma assisted combustion at atmospheric pressures by a high-voltage radio frequency generator | Institute of Combustion Technology, DLR Stutgart |
| 6 | Walter R. Lempert | Kinetic studies of plasma chemical fuel oxidation in nanosecond pulsed discharges by single and two photon laser induced fluorescence | Ohio State University |
| 7 | Allassane Seydou | Study of the hydrodynamic effects in plasma-flame interactions | Institut Pprime CNRS, Futuroscope |
| 8 | Da Xu | Temporal and spatial evolution of OH concentration in a lean premixed propane-air flame assisted by nanosecond repetitively pulsed discharges | EM2C, Ecole Centrale Paris |

## Poster session 3. Discharges and Kinetics

| | Presenting author | Poster title | Affiliation of presenting author |
|---|---|---|---|
| 1 | Gianpiero Colonna | Self-consistent collisional-radiative model for shock tube in Jupiter atmosphere | CNR IMIP Bari |
| 2 | Anna Dubinova | Simulating streamer discharges near dielectric materials | Centrum Wiskunde and Informatica, Amsterdam |
| 3 | Sami Goekce | Evaluation of active species production in a surface dielectric barriers discharge (SDBD) by OES | EPFL Lausanne |
| 4 | Carmen Guerra Garcia | Plasma dynamics under non-premixed combustion conditions: the Gas-confined Barrier Discharge concept | Massachusetts Institute of Technology |
| 5 | Sean McGuire | Nanosecond time-resolved 2 + 2 radar REMPI measurements performed in molecular nitrogen | Princeton University |
| 6 | Andrei Klochko | Experimental measurements of atomic oxygen concentrations in a capillary nanosecond discharge | LPP Ecole Polytechnique |
| 7 | Amath Lo | Energy transfers during the post-discharge of a nanosecond pulsed air discharge | CORIA, Université de Normandie |
| 8 | Evgeny Mintusov | Cavity ring-down spectroscopy measurements of $N_2(A^3\Sigma_u^+)$ species for v = 0, 1, 2 and 3 vibrational levels | EM2C Ecole Centrale Paris |
| 9 | Ivan Moralev | Spatial structure and induced gas dynamic disturbances of the dielectric barrier discharge in the constricted regime. | Joint Institute for High Temperatures, Moscow |
| 10 | Nikolay Popov | Fast gas heating in air discharge plasma at high dissociation degree of oxygen molecules | Skobelt'syn Institute of Nuclear Physics, Moscow State University |
| 11 | Florent Sainct | Experimental investigation of nanosecond repetitive discharges effect on water vapor dissociation at atmospheric pressure | EM2C, Ecole Centrale Paris |
| 12 | Sergey Stepanyan | Investigation of nanosecond surface dielectric barrier discharge and its application for initiation of hydrocarbon combustion | LPP Ecole Polytechnique |
| 13 | An-bang Sun | Understanding the inception of pulsed discharges | Eindhoven University of Technology |
| 14 | Thomas Unfer | MACOPA : A multi-physics simulation platform for plasma and combustion | IMFT |